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Casting Quality Improvement by Gating System Optimization

M. Bruna*, M. Galčík

Department of Technological Engineering, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia

* Corresponding author. E-mail address: rapture.marko@gmail.com

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Abstract

One of the main reason for decreased internal homogeneity of aluminium alloy castings is reoxidation. The resulting products of reoxidation are doubled oxides, so called "bifilms". Submitted paper deals with optimization of gating system design in order to reduce reoxidation processes taking place in mold cavity. Experimental work compares and evaluates three gating systems designs based on non-pressurized and naturally pressurized principles. Unconventional spin trap extension of runner was used in third design. Among the evaluated aspects were: mechanical properties, hot tearing index, visual inspection of average porosity amount, numerical simulation of velocity, turbulence and oxide amount. Paper aim is also to clarify the reoxidation phenomenon by visualization with the aid of ProCAST numerical simulation software. Results of mechanical properties and hot tear index clearly confirmed the positive effect of the naturally pressurized gating system with applied element for velocity reduction.

Keywords: Reoxidation, Gating system, Numerical simulation, Aluminium alloys, Mechanical properties

1. Introduction

Importance of aluminium cast alloys and their use in recent years reflects the demand for light-weight construction with maintaining good mechanical properties. Aluminium alloys castings have been rarely used in the safety-critical application despite of many positive characters. The reason is the high variability of mechanical properties. In 1987 Svoboda [1] made research from 14 independent foundries on 500 castings. The result showed that 84% of foundry defects are caused by reoxidation. There is no similar research recently and although it was focused on the steel castings, the impact of even larger extent can be expected for aluminium alloys.

Reoxidation is the term involving secondary and tertiary oxidation of liquid metal during metallurgy operations, filling process and solidification of the metal in the mold. Reoxidation processes arise mainly because of melt critical velocity associated with surface turbulence causing entrained defects formation (Fig. 1). These are principally (a) bubbles that in turn create bubble trails;

(b) bifilms; doubled over surface films, that act as cracklike defects; and (c) sundry entrained debris, collectively known as exogenous inclusions. [2]



Fig. 1. Scheme of the bifilm creation process

Campbell [3] defined the term "bifilms" and pointed out their negative potential affecting casting properties. Bifilms take a central role in pore formation as they can easily open up and inflates due to hydrogen diffusion into their inner environment and the surrounding pressure drop. One of the possibilities how to easily suppress the negative influence of reoxidation is by fundamental change of approach to the gating system design.

2. Experimental method

AlSi7Mg0.3 alloy was used for the experimental work, chemical composition is shown in Table 1.

Table 1.

Chemical composition of AlSi7Mg0.3

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
[wt. %]	7.3	0.15	0.03	0.1	0.3	0.07	0.15	bal.

Construction of the gating system is commonly divided into pressurized and non-pressurized gating systems, based on the so-called 'choke area'. In the pressurized gating system, the total cross section area of the gating system decreased towards the mold cavity and the gates acted as the choke. The purpose of such gating ratio is to fill up the runner and the sprue as quickly as possible and, therefore, reduce the risk of air aspiration in to the melt. This, however, may result in high velocity flow entry to the mold cavity leading to excessive melt turbulence. In unpressurized gating systems, this is counteracted by increasing the total cross section area of the gating system towards the mold cavity. Sprue base acts as the choke and the flow velocity and turbulence decreases towards the cavity. The drawback of unpressurized system is that the system may never run full resulting in air aspiration in the gating system. In the naturally pressurized gating system, the cross section areas of different parts of the gating system is selected in a way to correspond with the decrease in the melt velocity due to frictional losses as it travels through the gating system. The purpose of such design is to avoid high melt flow velocity and turbulence while keeping the gating system full during mold filling to avoid air aspiration.

The concept of naturally pressurized system is designed without the 'choke area' as close as possible to 1:1:1 ratio, so that the melt is in all places in direct contact with the mold walls (except for the flow tip) by natural backpressure in gating system due to friction. Although this concept has been known for a long time, its use in practice is rare because additional melt velocity reduction must be introduced. To reduce the melt velocity in naturally pressurized systems, the filters, extensions of the runner or spin traps are applied. Based on the literary analysis it appears that the satisfactory results will be achieved by ensuring the combination of all mentioned.

The first part of the experimental work is focused on the numerical simulation by ProCAST. Three types of gating systems were calculated and designed (Fig. 2). First systems is non-pressurized gating system (typically used for aluminium alloys – fig. 2A). Following two systems are based on the concept of the naturally pressurized gating system, Fig. 2B shows concept without runner extension and Fig. 2C represent system with spin trap extension. [4]

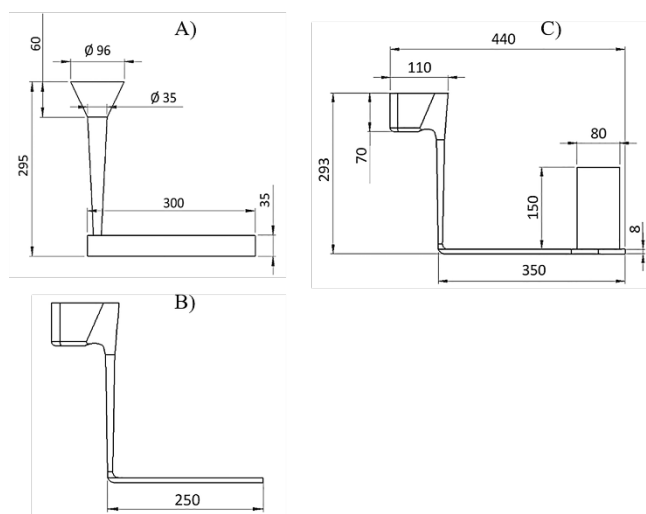


Fig. 2. Gating system design for experimental work a) non-pressurized gating system, b) naturally pressurized gating system, c) naturally pressurized gating system with spin trap extension

For the purposes of experiments, two types of castings were used. First casting design was intended for mechanical properties evaluation - Fig. 3a. Second casting shape is related to hot tear index evaluation - Fig. 3b.

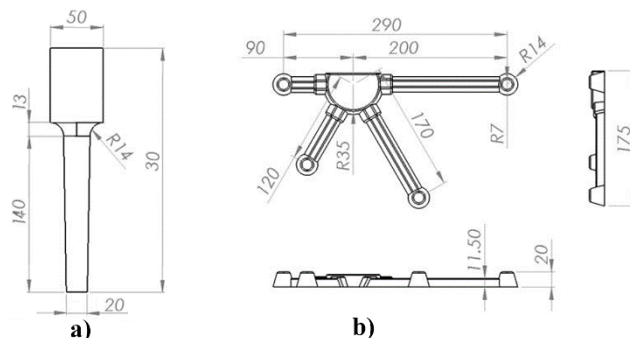


Fig. 3. Design of castings a) Mechanical properties b) Hot tear index

By the numerical simulations, mold filling and analysis of oxides amount were evaluated. Subsequently, real castings were produced to be able to compare results with the simulations. Castings were poured by gravity sand casting method (green sand). The melt temperature was 720 ± 5 °C poured to a non-preheated mold with temperature 20 °C. Three sets of castings from every mold design concept were made. Boundary conditions used during the simulations was with respect to a real casting conditions, including: metal chemical composition (alloy A356 from database), melt temperature (720 °C), mold composition (green sand from database) and temperature (20 °C), pouring height (tip of the ladle to pouring cup height 150 mm) and filling time (individual for each design based on measurement of time during experimental casting).

3. Numerical simulation and porosity evaluation

The tracking indicator for oxide amount was set to reference value [$0.5 \text{ cm}^2 \cdot \text{s}$]. Feature called "tracking indicator" in ProCAST v2019.1 allows to observe free surface of the melt in gating system (exposed to air) in real-time. Software keeps tracking the exposed surface area during the whole filling process, even when surface is entrained to the bulk of the melt. At each point of the free surface, its area is multiplied by the time. Actual value is cumulated to the previous timestep value. With the post-process visualization, it is possible to observe the reoxidation taking place in the gating systems during filling, as well as the probable distribution of the oxides in the final casting.

The result of the first variant (Fig. 4) shows imperfectly filled runner, a large area of surface layer is available for reoxidation and breaking waves, also the melt bounce back at the end of the runner, and the two surfaces are subsequently folded and joined, undeniably creating a large amount of bifilms.

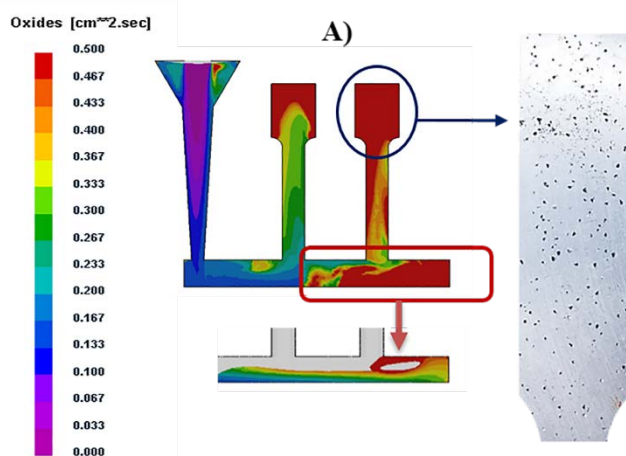


Fig. 4. Filling character and porosity inspection for design A)

The result of the melt flow rate analysis for the non-pressurized gating system showed a reduction of the melt velocity in the choke area, which ensured filling velocity in the gate area at subcritical values $0.33 - 0.45 \text{ m} \cdot \text{s}^{-1}$. Despite the positive velocity in gate area, the above mentioned negative effects are determining factors for a high degree of sample porosity.

In the case of a naturally pressurized gating system (Fig. 5), the place for turbulence is eliminated by a perfectly filled space in every point of the system. The critical place of this concept is the gate area because of the melt high velocity without any slowing mechanism. Velocity energy at the end of the runner is transferred to the gate area, where the splashes occurs, resulting in the extensive reoxidation. At this point, all benefits of a perfectly filled gating system during the filling are negated. Filling velocity in the gate area is above critical value ($0.63 - 1 \text{ m} \cdot \text{s}^{-1}$). After visual inspection it may appear that the porosity amount decreased compared to fig. 4, but after more accurate porosity evaluation (fig. 7) was proven that samples contain high amount of small pores, so-called "young bifilms". [5, 6]

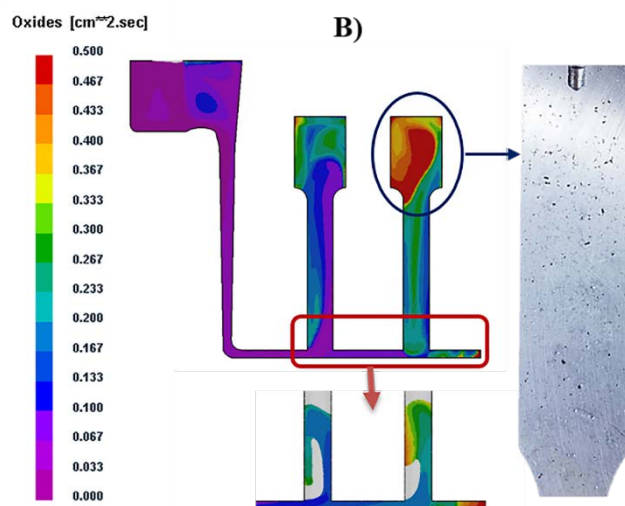


Fig. 5. Filling character and porosity inspection for design B)

The best result was achieved in the naturally pressurized gating system with spin trap extension of the runner (Fig. 6).

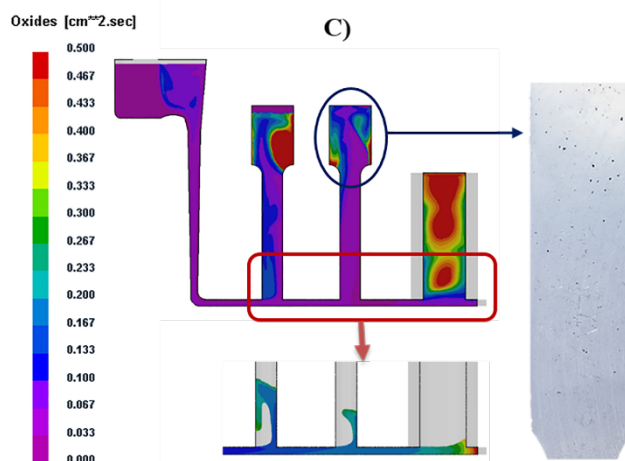


Fig. 2. Filling character and porosity inspection for design C)

The melt flow is directed to a spin trap, which ensures calm continuity of flow in the runner. Spin trap also causes flow velocity to decrease and the gases (or the non-metallic inclusions that are typically located at the front of the metal flow) should end up inside the spin trap.

Filling velocity in the gate area is subcritical ($0.43 - 0.5 \text{ m} \cdot \text{s}^{-1}$) and visual porosity inspection shows best results compared to previous designs.

More accurate digitalized quantitative evaluation was performed in order to determine average porosity for each sample. Six samples for each design was evaluated, at Fig. 7 can be seen samples taken from the second casting, positioned farther from the pouring cup. The presence of porosity was assessed based on area porosity evaluation. Macrostructure images were taken using an optical microscope. Subsequently, the captured images were processed by the QuickPHOTO INDUSTRIAL v3.1 software,

where graphic filters were set to highlight all pores on selected samples by red. Finally, the average percentage of porosity area within the selected samples were evaluated.

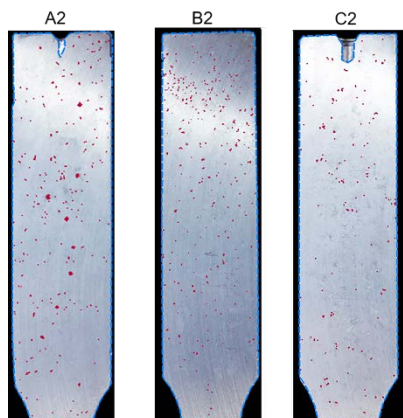


Fig. 7. Average porosity evaluation

Results shown at Fig. 8 represents a percentage area of the sample occupied by pores. Interestingly, design B) achieved increase in average porosity compared to design A). Pores in design B) are smaller in size but amount is increased, what indicates their are originating from later stages of mold filling during the spatter at the gate area. Design C) contains significantly smaller quantity of pores achieved by minimization turbulence occurrence associated with velocity reduction.

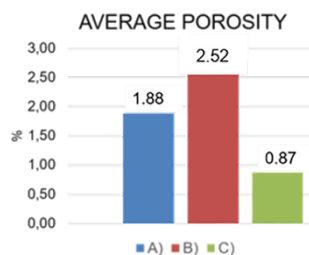


Fig. 8. Average porosity values

4. Mechanical properties and hot tearing index evaluation

In comparison with other types of inclusions, the presence of bifilms has a significantly more negative impact on mechanical properties, what can be attributed to the brittleness (mainly of older bifilms) and residual gas phase contained in the interior of the bifilm.

The results from 6 samples for each design clearly point out that the highest tensile strength values was obtained by using the naturally pressurized gating system with spin trap. The processed results from the arithmetic mean of the measured values, are presented in Fig. 9. Based on the numerical simulation, it can be assumed that the lowest tensile strength for design B) is the result of the high content of young bifilms, due to the spatter of the molten metal at the entrance to the mold cavity in the gate area.

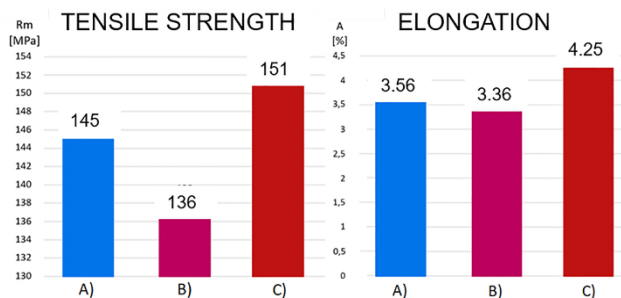


Fig. 9. Results of the tensile strength and elongation

The average elongation of test samples was $3 \pm 0.5\%$, except for the naturally pressurized gating system with spin trap where elongation reached above 4%. It can be seen that decrease of elongation for variant B) is not so significant compared to decrease of tensile strength, what can be explained by the fact that young bifilms are not so brittle and thus less affect the elongation.

Second set of castings were used for hot tears index (HTI) evaluation. HTI criterion is determined by character and amount of tears in four arms with different length. From each design was cast three samples, which was removed from the mold after ten minutes for visual evaluation. The HTI is defined according to equation (1):

$$HTI = \frac{NOT \times \sum WF}{NOC} \quad (1)$$

Where NOT is number of tears, WF is weighting factor and NOC is number of casted samples. The value of the weighting factor depends on the nature and size of the individual hot tear. Fig. 10 represents coefficient values for different types of hot tears. [7]

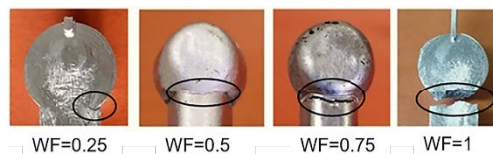


Fig. 10. Weighting factor values

HTI values are shown at fig. 11. It can be seen that the HTI for design C) significantly decreased to almost zero value. In this case we were unable to achieve complete tearing of the arm (IF=1), what was common for design A) and B). As the Campbell claims [8] The phenomenon of hot tearing during the solidification of castings can be eliminated by the reduction of bifilms in the liquid. This was achieved by providing a filling system design for the casting that does not reintroduce bifilms.

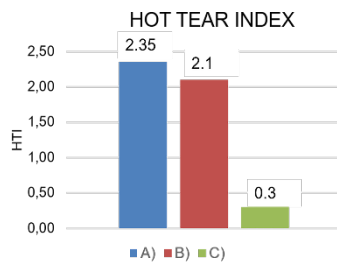


Fig. 11. Hot tear index values

5. Conclusions

Numerical simulation proven that filling systems designed to follow the shape of the falling stream (naturally pressurized system) are successful to reduce the conditions for forming entrainment defects.

Using of spin trap reduces the critical velocity of flow at the gates to subcritical values, in its progress along the runner, the leading tip of the molten metal (with a certain amount of bubbles) is directed tangentially into a vertical cylinder, as a trap for bubbles, and as a mechanism to gradually increase back pressure to aid the filling of gates with subcritical velocity metal.

The mechanical properties evaluation confirmed the positive effect of the naturally pressurized gating system, but only when proper velocity reduction element is used. In case when velocity was not reduced, naturally pressurized gating system achieved even worse mechanical properties than the common non-pressurized system. Hot tear index evaluation clearly confirmed the positive effect of the naturally pressurized gating system, leading to almost “hot tear free” casting.

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